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35 word or less abstract:

We present studies of EMP generation, particularly the effects of various processes (geomagnetic rotation, drag, and scattering) on the rise time and amplitude. We describe plans for and progress toward a comprehensive 3-D EMP code.

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Studies of EMP generation using a Liénard–Wiechert formulation, and progress toward a 3-D EMP code

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We describe studies of the generation of electro-magnetic pulse (EMP) fields under the idealized conditions of a delta-function gamma pulse, a spherical cap of Compton electrons located at a common radius from the burst, and the absence of the conduction current. Various processes (geomagnetic rotation, drag, and scattering) contribute to the time derivative of the Compton current density, which appears as the source term in the Liénard–Wiechert expression for the radiation field. These processes are considered separately and in combination, and their influences on the waveform of the EMP assessed. We also describe plans for and progress toward a comprehensive 3-D EMP code, which is to employ recently developed numerical methods and is to offer a variety of models, including the Liénard–Wiechert formulation described here.

I. Introduction

A project aimed at the development of a comprehensive and modern 3-D simulation code for electro-magnetic pulse (EMP) formation and propagation has been initiated at LLNL. Building upon the open-source Warp particle-in-cell code framework[1,2,3] (developed by members of this team and collaborators) and a selection of newly invented methods, we are developing a suite of physics models and operating modes tailored for detailed EMP studies.

In order to be able to benchmark the new code, and to develop a deeper understanding of the statistical requirements for particles and the necessary spatial and temporal resolution, we have developed a Liénard–Wiechert ("L-W," henceforth) evaluator and applied it to a number of model problems. In the L-W formulation, the accelerations experienced by the Compton electrons establish the generated electromagnetic field. This work has clarified aspects of EMP generation, in particular the roles of the various physical processes (geomagnetic rotation, drag, and scattering) that determine such accelerations. We have evaluated waveforms of the EMP for representative cases under idealized conditions: a delta-function gamma pulse, a spherical cap of Compton electrons that begin their motion at a common radius from the burst, and the absence of the conduction current. These conditions exclude factors that serve to increase the rise time (finite-duration gamma pulse, thick active layer), and one that may shorten the rise time (conductivity of the medium). We are especially interested in understanding the lower limits to the pulse rise time.

Section II below outlines our L-W solver and presents representative results. Section III compares the synchrotron radiation generated in 2-D planar geometry by a gyrating infinite rod of particles, as computed via a finite-difference time-domain (FDTD) EM simulation, to that obtained via our L-W solver applied to a "stack" of electrons. Section IV summarizes plans for and progress on the new code.

II. Liénard–Wiechert solver

The L-W solver initializes a large number (typically 1 to 10 million) of simulation particles, each representing many Compton electrons, on a spherical cap using a non-random (but not entirely regular) "quiet load" prescription; the physical areal density of electrons is set by the user. All are launched at the same instant using a Klein-Nishina distribution of energies and angles, under the assumption that they have been created by a monoenergetic set of gamma rays (whose energy is set by the user). The electron trajectories are advanced in time over a series of time steps, including the effects of geomagnetic rotation, along with drag and random scattering in air using rates from the NBS. At each step the EMP field due to an electron is evaluated at the observer's position using the L-W formula and the electron's instantaneous acceleration. We assume a uniform geomagnetic field along the y-axis, and the LOS along the z-axis.

Then, symmetry ensures that the dominant component of the EMP magnetic field is directed along the y-axis, with other components at small levels and due to fluctuations. So, for efficiency, we compute only B_y (and infer the magnitude of the radiated E field using $|E| = cB_y$).

The major complication of this approach is that the distance from each electron to the observer, at each timestep, is unique; the fields generated at source time t_s by spatially distributed particles do not arrive at the same observer times (t_{obs}). Thus, at each step, for each electron, we compute $t_{obs} = t_s + r(t_s)/c$, where $r(t_s)$ is the instantaneous distance between the moving electron and the fixed observer. Since the observer sees, at any instant, the fields generated by many electrons, the individual contributions, each of which arrives at its own unique t_{obs}, are deposited into a common set of "t_{obs} bins" using a scatter-add procedure identical to that used for depositing the charge in a 1-D particle-in-cell plasma simulation. We display the field as a function of the delayed time $\tau_{obs} = t_{obs} - t_{obs}$(first observed photon).

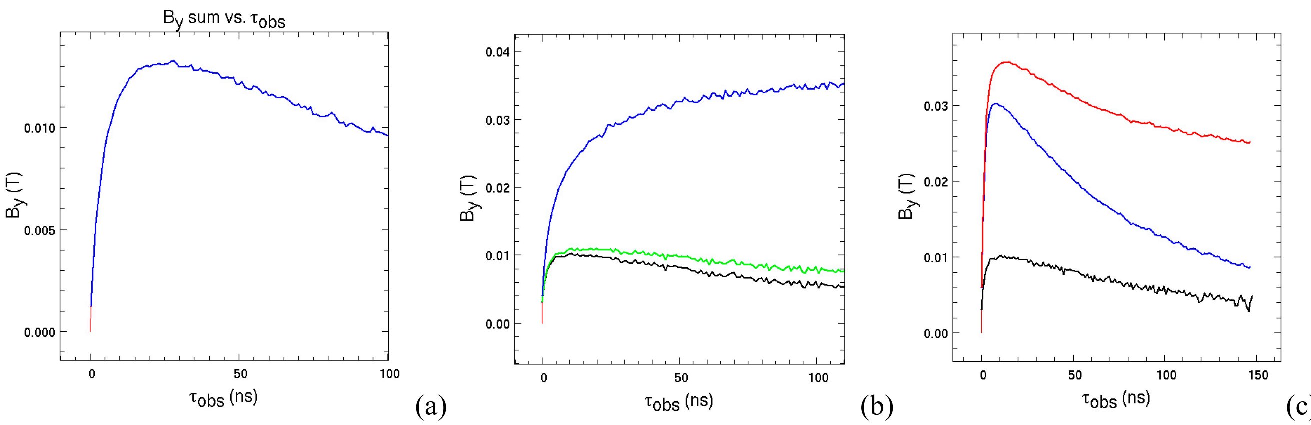

Figure 1. Sample output obtained using L-W solver (see text).

Figure 1 summarizes representative cases explored via our L-W solver. Note that the absolute magnitudes of the fields plotted have no significance; we do not include dissipation, so the field strength scales linearly with the user-specified sheet density of Comptons (here, $6.5\text{x}10^{14}$ m^{-3}).

Panel (a) of the figure displays results for a spherical-cap Compton electron source of transverse extent 1.2 km (LOS-to-edge), at altitude 30 km, driven by 1.6 MeV gamma rays from a burst at 100 km. The L-W solver shows a 23 ns time-to-peak for the EMP observed at sea level.

Panel (b) of the figure shows results from a similar study using 3 MeV gamma rays, altitude 20 km. In the lowermost (black) curve, all terms are retained in the dynamical equations and in the acceleration used in the L-W expression. With geomagnetic turning, the drag-induced accelerations acquire, on average, a component transverse to the LOS, and this component contributes negatively to the EMP. In the intermediate (green) curve, that drag contribution to the acceleration used in the L-W formula has been suppressed. In the uppermost (blue) curve, the geomagnetic force has been removed from the equation of motion (but retained in the acceleration used in the L-W formula); thus, the synchrotron "beacon" remains, on average, more nearly directed toward the observer. Here, the drag contribution to the acceleration used in the L-W formula has almost no effect; without the gyration, its direction is set by scattering alone and is uncorrelated from electron to electron.

Panel (c) of Fig. 1 shows the results of another study using the same parameters. Again, all terms are retained in the black curve (lowermost). In the red (uppermost) curve, scattering has been suppressed and the drag term has been omitted from the L-W expression, significantly enhancing the field at the observer. Finally, in the blue curve (middle), scattering has been suppressed but the drag term has been retained in the L-W expression; the negative-lobe contribution from drag pulls the signal down.

III. Synchrotron radiation in 2-D, as computed via FDTD and L-W methods

When we first simulated synchrotron radiation using Warp's FDTD solver in 2-D (x,z) geometry, the results surprised us. Observers do *not* see the classical single-particle beacon-and-lobe structure sweep by, in the sequence: small negative signal, large positive, small negative. This is because, in 2-D, a "particle" is really a rod (or a stack of particles) with infinite extent along y. The delayed positive beacons from large-|y| sources overwhelm the negative lobes from small-|y| sources, so the trailing negative lobe associated with point-particle gyration does not appear. This physics is inherent in the structure of the Maxwell equations in 2-D. With this in mind, we compared the results from Warp and the L-W calculation. See Fig. 2. In Warp we used a timestep size $\Delta t = 0.6515$ ns, and a grid with 1536 cells along x, 5632 along z, and cell sizes $\Delta x = \Delta z = 0.1953125$ m. The particle starts at the left of the blue circle, moving in the –x direction. For the L-W calculation, 64001 source electrons were stacked from y = -2000 m to y = 2000 m. Agreement is good; the Warp result converges to the L-W one as the grid resolution is increased.

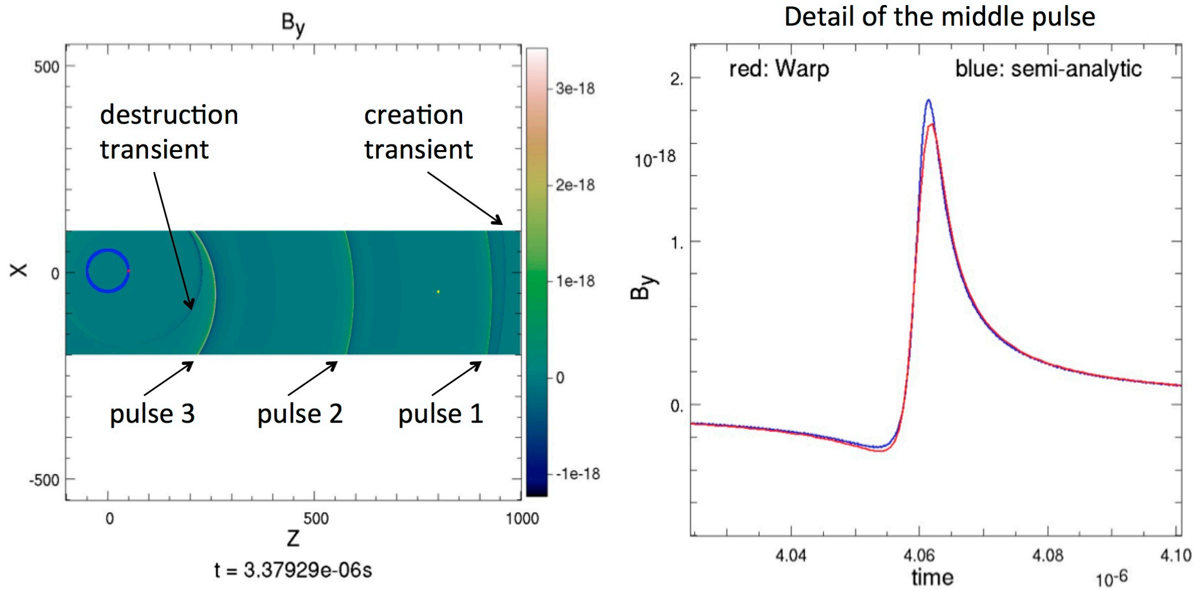

Figure 2. (left panel) snapshot of FDTD simulation of the fields from a moving rod of charge, which begins and ends its gyration suddenly, leading to creation and destruction transients. The observer is at the position of the yellow dot; (right panel) time history of the second pulse as it passes by the observer (lower curve, red), and the semi-analytic L-W result (blue).

IV. Progress toward an advanced EMP code

Under the auspices of LLNL's Laboratory Directed Research and Development program, we are developing a new EMP code, building on the Warp code framework, and incorporating the additional physics required for EMP problems. This leverages extensive prior work by LLNL, LBNL, and collaborators on the development and use of the code for other applications. Warp offers electromagnetic and electrostatic particle-in-cell models in various geometries and dimensionalities, and has been benchmarked on ion beam experiments, laser acceleration tests, anti-hydrogen traps, and other systems. The Warp framework includes a rich set of physics extensions to the Python language, and is thus user-programmable and "steerable." Input files are programs written in Python that invoke Warp physics models. The intensive numerical calculations are carried out in Fortran, with a custom-made run-time database manager handling large arrays. The Fortran and Python layers are connected using the Forthon[4] package, so that the user has access to all code variables and routines, as desired.

We are well along in incorporating the required additional physics models into this framework, specifically: the ability to track the incoming gamma rays, their scattering and energy loss, and the gamma-induced creation of Compton electrons; descriptions of the atmosphere and geomagnetic field; the creation of conduction electrons, and thus of a temporally and spatially varying conductivity; and the scattering and drag forces on Compton electrons. We plan to include a selection of models, including the Liénard–Wiechert one described here, for insight and to aid comparison versus CHAP[5] and other codes.

Recently, advanced methods have been developed for laser-plasma acceleration and other problems. These methods appear to be well suited for application to the (surprisingly similar) EMP problem, and we are exploring their use. They include: (1) Operation in a Lorentz-boosted frame[2] (via a rotation in space-time); this brings disparate scales closer together and reduces computational effort, and has been employed for applications such as laser-plasma accelerators and particle beams interacting with electron clouds. (2) Application of mesh refinement to a gridded Maxwell equation solver, coupled with a modern outgoing-wave boundary condition implementation;[2,3] this can facilitate simulation of an EMP pulse in free space as it impinges on terrain or structures. (3) Parallelization of the pseudo-spectral approach to solving the Maxwell equations has recently been achieved.[6] This approach minimizes numerical dispersion and can thus aid in simulating the propagation of EM signals over large distances.

We look forward to bringing this new tool to maturity and applying it to realistic problems.

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